ADVANCED ASPIRATING SEAL

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ADVANCED ASPIRATING SEAL

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Stein Seal Company, Kulpsville, PA
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Stein Seal Company developed a 14.7” and 36” advanced aspirating seal for GE Aircraft Engines. The seal is developed for a thrust balance application in gas turbine secondary flow path. Stein built and tested the 14.7” advanced seal. Tests included static tests, dynamic tests with rotor runouts up to .010” (TIR), and sand ingestion tests. All test were conducted at room temperature.

The advanced aspirating seal provides hydrostatic operation with low leakage and high gas film stiffness at high differential pressures and high temperatures. The all metal seal has the ability to operate at high temperature with large rotor runout. The design process and comparison to the original aspirating seal will be discussed along with recent test data.

The advanced aspirating seal performed successfully during extreme rotor runout tests up to .010” (TIR), whereas the original aspirating seal could not tolerate a rotor runout above .005”.

Agenda / Goals

Agenda
- Design Goals & Operating Conditions
- Seal Operation
- Analysis - Original & Advanced Seal Design
- Rig Test Results
- Performance Attained

Goals
- Develop 14.7” & 36” Advanced Aspirating Seal
- Meet Leakage and Performance Goals
- Increase Gas Film Stiffness
- Increase Seal’s Ability to Follow Extreme Rotor Runouts
- Build & Test 14.7” Seal

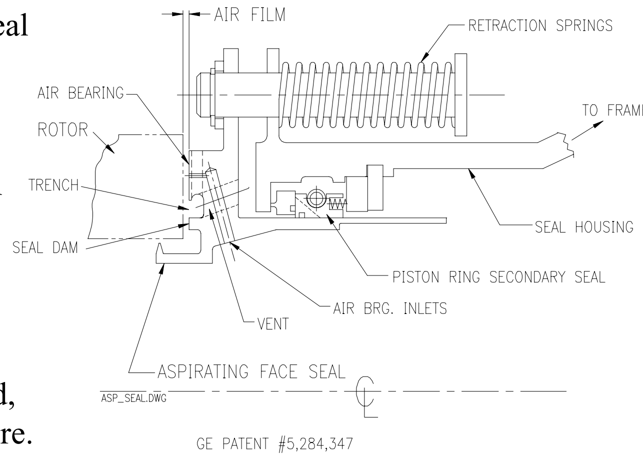
The advanced aspirating seal is developed by Stein Seal Company in conjunction with GE Aircraft Engine Company. The advanced seal offers improvements beyond the original aspirating seal design built several years ago.

Two seal sizes were studied and include a 14.7” seal and a 36” seal. The 14.7” seal was built and tested. The 36” seal was designed but not built.

The topics for discussion and program goals/objectives are included above.

What is an Aspirating Seal?

- A Hydrostatic Face Seal
  - Rides on a film of air
    - » 1.5 to 2.5 mils
- Provides <u>controlled</u> leakage throughout all operating conditions.
- Performance does not degrade over time.
  - non-contacting seal
- Operates at high speed, temperature, & pressure.
- Designed to replace labyrinth and brush seals



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This slide shows the aspirating seal's major parts and features. The aspirating seal is a replacement for labyrinth and brush seal applications.

GE patent #5,284,347

Requirements / Challenges / Application

Operating Conditions:

Shaft Speed:	392 ft./sec.
△P.:	100 psid
Air Temp.:	750 °F
Leakage:	~ 2.0 scfm/psid
Seal Life:	Unlimited (non-contacting)

Applications:

- Gas Turbines (Aviation & Land)
  - Thrust Balance
  - Compressor Discharge
  - LPT
- Labyrinth & Brush Seal Replacement

Challenges:

- Improve gas film stiffness
- Maintain uniform gas film clearance during all conditions
- Maintain low leakage performance
- Provide infinite seal life
  - Non-contacting, all metal design

Funding:

- Provided by GE Aircraft Engine
  - Developed under NASA's AST program (Glenn Research Center)
    - » IHPTET initiative

Target Engines:

- GE-90, UEET

The operating conditions are shown and are representative for the 36" seal.

The seal is developed under NASA's AST program and funded by GE Aircraft Engine Company.

The advanced seal requires an improvement to the gas film stiffness as compared to the original seal. Low leakage and uniform gas film clearance are requirements for the all metal non-contacting seal design.

The advanced aspirating seal is targeted for gas turbine secondary flow applications (I.E.: compressor discharge, LP turbine). The GE-90 and UEET engines are targets for seal integration. The aspirating seal is a replacement for brush seals and has significant leakage improvement as compared to brush seals. The aspirating seal leakage is approximately 20% of a brush seal.

Two Seal Sizes Developed:

Sub-Scale Seal

- 14.7” Seal (Rig Seal)
  - Optimized design
  - For rig testing at Stein
  - Utilizes highest gas film stiffness and fits GE-90 rotor envelope

Full Size Seal

- 36” Seal (Paper study)
  - Seal targeted for GE CRD test rig
  - Utilizes existing rig rotor with minor changes
  - High gas film stiffness not realized due to rig rotor constraints

<u>14.7” seal</u>

This seal has the widest face configuration that fits the GE-90 rotor envelope. The gas film stiffness is greatly improved compared to the original aspirating seal. This seal configuration was chosen for rig tests due to the performance increase.

The flow diverted is not required on the rotor.

<u>36” seal</u>

This seal has a radial face configuration that fits the existing rig rotor face on the GE CRD rig. This seal was developed to demonstrate that an improved aspirating seal could be developed to fit an existing test rig. This seal , to date, has not been built.

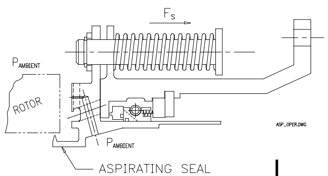
<u>Rotor flow diverter</u>

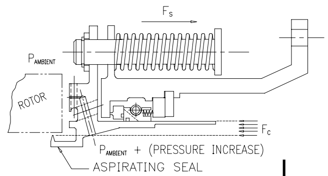
The rotor diverter is a metal protrusion on the rotor face that projects into the seal's trench (annulus) between the seal dam and air bearing. The rotor flow diverter is required of the 36" seal. The 14.7" seal does not require the rotor flow diverter.

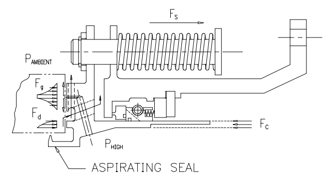
The function of the flow diverter (when required) is to direct the seal dam gas flow into the radial and axial vent slots on the seal. Without the diverter, the gas path may tend to go radially outward, across the air bearing, and disrupt the flow and performance of the air bearing. It may be possible for the seal not to close without the flow diverter.

Seal Operation

Force Balance Equation, Fc = Fg + Fd + Fs + Inertia + Friction







START-UP / SHUT-DOWN:

(0 PSID)

- Springs retract seal open
- Large gap exists between seal and rotor face

AT PRESSURE INCREASE:

(< 3 PSID)

- Pressure builds and seal starts to close towards rotor.
  - Pressure drop occurs across balance dia. and laby tooth
  - Closing force overcomes retraction spring and friction forces
- Gap between rotor and seal face decreases

WITH PRESSURE DIFFERENTIAL:

(> 3 PSID)

- Pressure builds and seal closes toward rotor
  - Retraction spring force, friction force, and inertia forces are overcome
- As seal approaches rotor
  - Pressure drop occurs across seal dam
  - Air bearing force is established
- Laby tooth is no longer the primary pressure breakdown mechanism
- Seal is in equilibrium (1.5 to 2.0 mils gap)
  - Closing forces = Opening forces

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The seal operation is characterized by non-contacting operation.

Start up / Shut down:

At rest, the seal is retracted open by springs. This pulls the seal away from the rotor. At this position the seal has no pressure drop across the seal.

At pressure build up:

As pressure builds, the closing force starts to increase, overcoming the retraction spring forces and the friction and inertia forces. The pressure force is established by the area created by the balance diameter and the laby tooth (located beneath the rotor.)

At full pressure:

The seal is in equilibrium at 1.5 top 2.0 mils. The closing force equals the opening force. The closing force is established by the area created by the balance diameter and the seal dam ID. The opening force is created by the air bearing force. This force tends to open the seal.

Tasks Performed

1. Parametric Study
   - Varied seal features to yield best performance gain:
     - » Seal dam, gas bearing, & trench geometry
2. Gas Bearing Analysis & Rig Tests
   - Analysis performed by Wilbur Shapiro, Inc.
     - » NASA GFACE Code
   - Rig tests validated analysis
3. CFD Analysis (CFDRC Corp.) performed on 14.7" & 36" seals
   - 14.7" Seal: Rotor flow diverter not required
   - 36" Seal: Rotor flow diverter is required
   - Operating Gap: .0015" to .0020"
4. Optimized Seal Features:
   - 36" Seal: .550" gas bearing, .050" dam, .180"trench
   - 14.7" Seal: 1.250" gas bearing, .250" dam, .450" trench
5. Rig Tests (Sub-Scale seal)

Parametric design studies looked at all possible seal configurations that would show improved seal performance as compared to the original aspirating seal. Features that affect seal performance include:

Size and placement of the seal dam and air bearing

Number of air bearing holes, hole diameter, and number of rows of holes, and hole spacing

Seal aspirator tooth placement

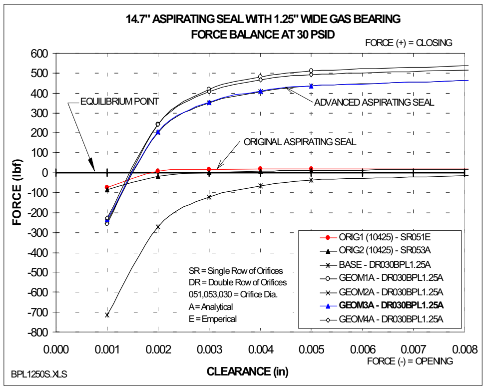
Gas bearing analysis and static rig tests were performed to determine the gas bearing performance. Wilbur Shapiro, Inc. performed the gas bearing analysis. The static gas bearing rig tests were used to correlate the NASA GFACE seal code and Coefficient of Discharge, Cd.

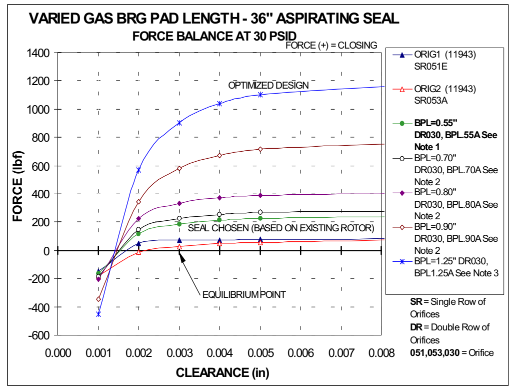
The optimized seal configurations for both seal sizes are shown. The 14.7" seal has the widest radial face as it has the optimum gas bearing stiffness per unit length. The 36" seal fits the existing rig rotor at GE CRD.

Computational Fluid Dynamics (CFD) was performed on both seal sizes. CFDRC of Huntsville, Alabama, performed these studies. Conclusions showed that the rotor flow diverter was required on the 36" seal but not required on the 14.7' seal. The seals operate properly with a gas film of 1.5 to 2 mils.

Analytical Summary - Force vs. Clearance at 30 psid

14.7” & 36 “ Seals





Advanced Seal has:

- Higher Gas Film Stiffness vs. Original Seal
- Improved load capacity
- Steep “Force vs. Clearance” slope at Seal Equilibrium point yields:
  - Small change in clearance = Large Restoring Force
  - High stiffness permits seal following during high rotor runouts

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The aspirating seal operates at an equilibrium point where the gas film is maintained at 1.5 to 2.5 mils.

Seal equilibrium point is where Force = 0 lbf. on the Y-axis. The operating gas film clearance is determined where the curve line cross the equilibrium point.

Steep line slopes are desirable since any change in clearance is a correspondingly high change in force.

The original aspirating seal configuration (solid circle) has a less steep slope as compared to the improved aspirating seal configuration (open triangle).

Gas bearing face width comparison:

.440” Original aspirating seal

1.250” Advanced aspirating seal

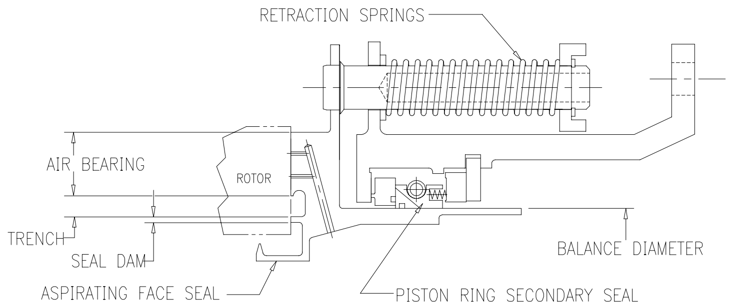
Gas film stiffness improvements are gained compared to the original seal design:

14.7” seal: 5.5 : 1 greater stiffness vs. original seal

36” seal: 1.7 : 1 greater stiffness vs. original seal (dictated by rotor size)

36” seal (optimized design): 6 : 1 greater stiffness vs. original seal

Seal Dimensions – 14.7” & 36” Seals



DIMENSION	SEAL SIZE	
	14.7”	36”
AIR BEARING WIDTH	1.250”	.550”
TRENCH	.450	.180”
SEAL DAM	.250”	.050”
BALANCE DIAMETER	14.700”	36.160”
ORIFICE DIA	.030”	.030”
ORIFICE SPACING	.851”	.806”
NUMBER OF ROWS	2	2
DIVERTER KNIFE REQ'D.	NO	YES

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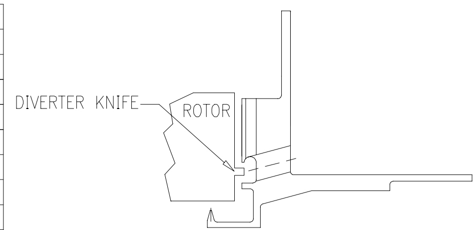

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Dimensional comparison between the 14.7” and 36” advanced aspirating seals.

The balance diameter defines the nominal seal size.

The gas bearing for the 14.7” seal offers the best gas film stiffness improvement as compared to the original aspirating seal. This is due to the wide gas bearing face and placement of the seal dam and air bearing relative to the seal balance diameter.

The gas bearing for the 36” seal is the best size that fits the existing test rig rotor at the GE CRD facility. If space permitted a larger rotor, then a wider gas bearing face would be utilized. A wider gas bearing would improve the gas film stiffness.

Each seal has a double row of gas bearing orifices for optimum gas film stiffness for the space permitted.

It is important to note that the 14.7” seal does not require the rotor diverter knife, whereas the 36” seal does require the rotor diverter knife. CFD analysis dictated the rotor diverter knife requirements.

Analysis - Air Bearing Stiffness Comparison

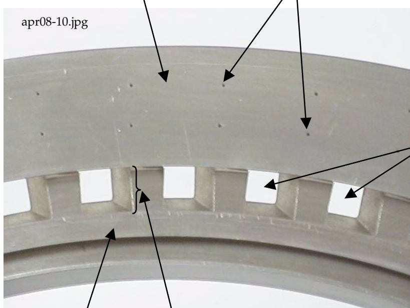
- Improved Gas Film Stiffness (based on 30 psid)
  - 14.7” Advanced Seal Stiffness 5.5 > Original Seal
  - 36” Improved Seal Stiffness 1.7 > Original seal
    - » Seal fits existing rig rotor face
  - 36” Advanced Seal Stiffness 6.0 > Original seal
    - » Optimized design, fits GE-90 engine
- Improved Seal Stiffness Benefits:
  - Improves load support
  - Large servo force restores seal to equilibrium
  - Steep “Force vs. Clearance” slope at Seal Equilibrium point yields:
    - » Original seal has shallow “Force v. Clearance” slope
  - Seal tracks extreme rotor runout

This slide shows the air bearing stiffness summary highlights.

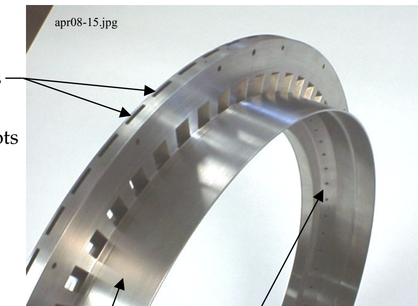
Important points here are:

1. The advanced seal has high gas film stiffness compared to the original aspirating seal.
2. The 36” seal designed for the GE CRD rig has a slightly improved gas film stiffness due to the space limits of the existing rig rotor.
3. The 36” seal for GE-90 space envelope does have a significant gas film increase as compared to the original aspirating seal.
4. Steep slopes for “Force vs. Clearance” is desirable as this will provide the largest restoring force to keep the seal in equilibrium.
5. Large variations in rotor runouts can be accommodated if seals have high gas film stiffness.
6. Advanced aspirating seals have identical leakage and film gap characteristics compared to the original seal.

Seal Features - 14.7” Advanced Seal



Face View

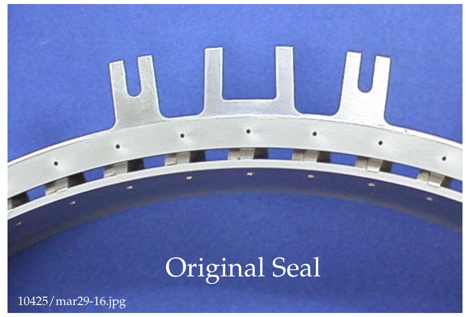


Rear View

The photographs show the 14.7” aspirating seal features

Material: 410 stainless steel

14.7” Aspirating Seal Comparisons



Seal Dam:	.250”	0.100”
Bearing pad:	1.250”	0.400”
Orifice dia.:	0.051”	0.053”
# Orifices/ Row:	60	60
# Row of Orifices:	Double row	Single Row
Trench width:	0.450”	0.150”

This slides shows the features of the advanced and original aspirating seals.

Rig Tests Performed

1. Gas Bearing Static Tests
2. Gas Film Calibration / Verification
   – Establish film clearance at operating pressure
3. Performance Mapping
   – Static/Dynamic tests
   – Speed and Pressure traverses
4. Rotor Runout Tests
   – 5 mil & 10 mil rotor (one per rev)
5. Flight Cycle Tests
   – GE-90 Conditions
6. Sand Ingestion (Original Seal)
   – 0 to 10 micron particle size, 1/3000 lb/sec flow rate

The rig test series is described in this slide.

The static gas bearing rig is a small sub-scale rig (~ 4” dia.) that is used solely for gas bearing testing. This affords quick part change-out that yields performance curves for various bearing configurations.

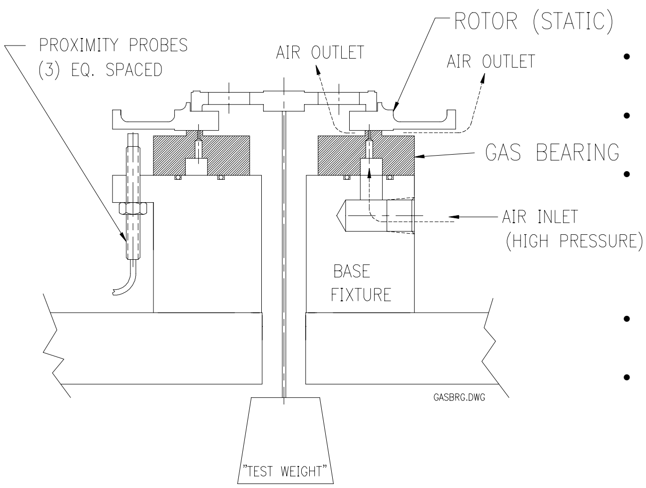
The dynamic rig is capable of testing the 14.7” aspirating seal to the conditions of the full size 36” seal parameters. Hot tests were not conducted on this rig.

Gas film calibration tests are used to assess the leakage performance with fixed film clearances between the rotor and seal face. Clearances are achieved by the use of shim stock material that is cemented to the rotor face at equidistant positions.

Rotor runout tests are performed to simulate gas turbine rotor whirl on a “one per rev” cycle.

Proximity probes measure the gas film clearance. Seal leakage is also measured on both static and dynamic test rigs.

Static Gas Bearing Rig



- Features the Gas Bearing portion of the seal (F_g)
- Test weight simulates the seal closing force (F_c)
- Tests provide data for Pressure vs.:
  - Leakage
  - Film clearance
  - Load capacity
- Data used to validate NASA GFACE code
- Sub-scale rig permits quick bearing change-outs for alternate bearing faces:
  - Multiple orifice rows
  - Orifice hole size and spacing

Static gas bearing test rig for sub-scale testing.

The rig is used to collect information such as:

Leakage vs. pressure

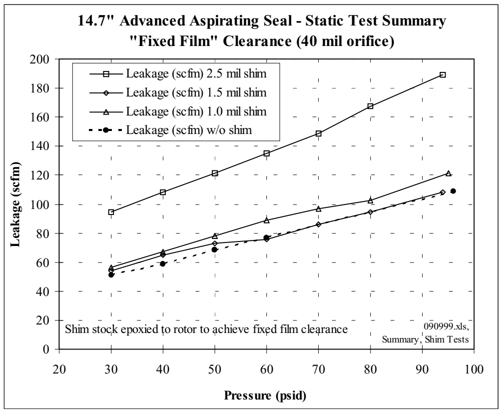
Film clearance vs. pressure

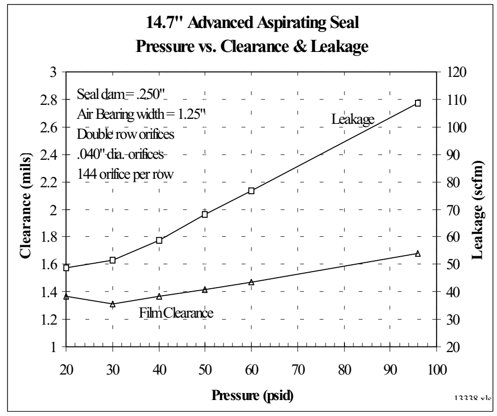
Proximity probes measure the gas film clearance.

Gas flows into the fixture and exhausts on either side of the gas bearing face. The test weight simulates the seal closing force at the rated pressure differential.

The data from this rig is used to correlate the NASA GFACE seal code.

Static Test Results – Advanced Seal





Gas Film Calibration Test:
- Gap set with shim stock
  - Calibrate prox probes
- Film gap = 1 mil at 30 psid
  - Slightly less than analysis

<u>Result:</u> Enlarge air bearing holes

Air Bearing holes enlarged:
At 30 psid:
- Film gap = 1.3 mils (static test)
- Film gap = 1.5 mils (analysis)
- Actual gap < Theoretical gap

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The two graphs represent the 14.7" seal performance on the dynamic test rig. Leakages include the primary face seal and the piston rig secondary seal.

Both graphs represent Pressure Differential vs. Seal leakage.

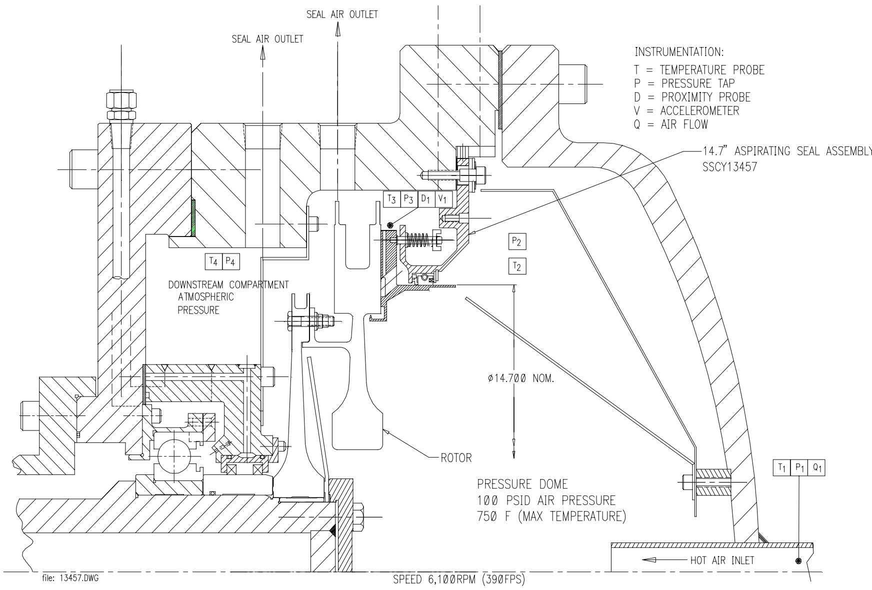
<u>Left graph</u>

This graph shows the seal leakage for the "fixed film" calibration tests. The solid lines represent the "fixed film" performance, while the dotted line represents the seal performance allowing the seal to float at its equilibrium point. In this graph, the film clearance is slightly less than 1 mil, running parallel to the 1 mil "fixed film" clearance test curve. The conclusion of this test shows that the actual film clearance is less than the theoretical film clearance for the same given pressure. The result of this test lead to an enlarged air bearing hole diameter, which will permit the seal to operate at a larger film clearance.

<u>Right graph</u>

This graph shows that the seal performance with enlarged air bearing holes (.040" dia.). The gas film clearance is approximately 1.3 mils at 30 psid. The analysis shows the gap is 1.5 mils at 30 psid, therefore, the analysis overstates the film clearance.

Dynamic Test Rig - 14.7” Aspirating Seal



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During operation the high pressure air enters the rig pressure dome through the air inlet pipe at the far right side. At 0 psid the seal is retracted open by mechanical springs, pulling the seal away from the rotor leaving a .090” gap. As pressure builds to approximately 3 to 4 psid, the seal is aspirated closed towards the rotor, overcoming the retraction spring force and piston ring friction force. The gas film is established between the rotor and seal face: 1.5 to 2.5 mils.

<u>Test conditions:</u>

Shaft speed: 6,100 rpm (390 fps)

Pressure differential: 100 psid

Temperature: ambient

Instrumentation includes:

(3) proximity probes (gas film measurement), mounted on the seal and aimed at the rotor tip face

(1) Accelerometer (mounted on seal to measure axial displacement caused by rotor runout)

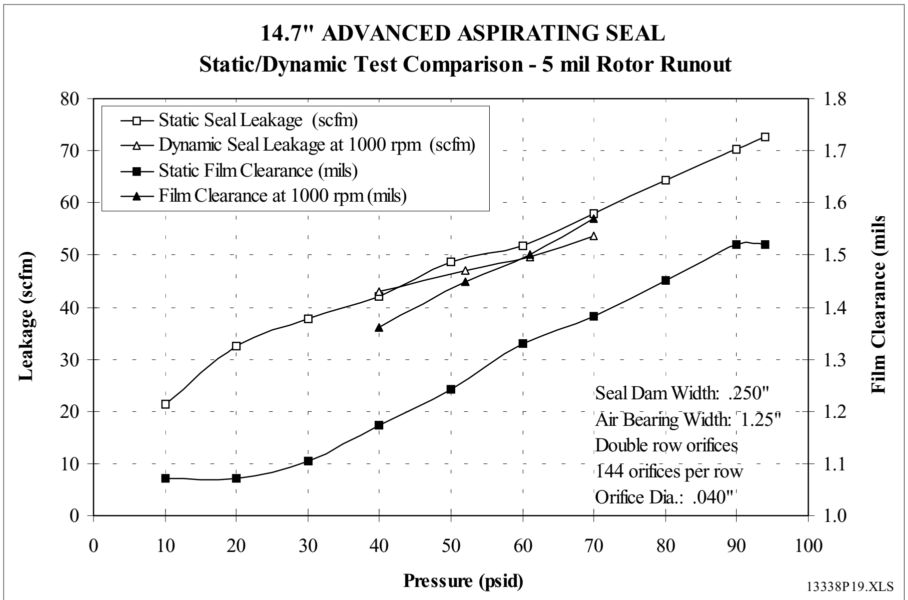
(2) Accelerometers mounted on rig bearings for rig monitoring

Various thermocouples for dome temperature, surrounding rotor temperature, bearing oil sump temps., etc.

Various pressure taps for dome pressure, bearing oil pressure, etc.

Rotameter: seal leakage

Static / Dynamic Leakage Comparison



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This graph depicts the static and dynamic seal performance for Pressure vs. Leakage and Film clearance. The shaft speed for the dynamic test was 1,000 rpm (65 ft./sec.)

Leakage and film clearance are closely matched for static and dynamic test conditions.

The rotor face runout during the dynamic test was 5 mils.

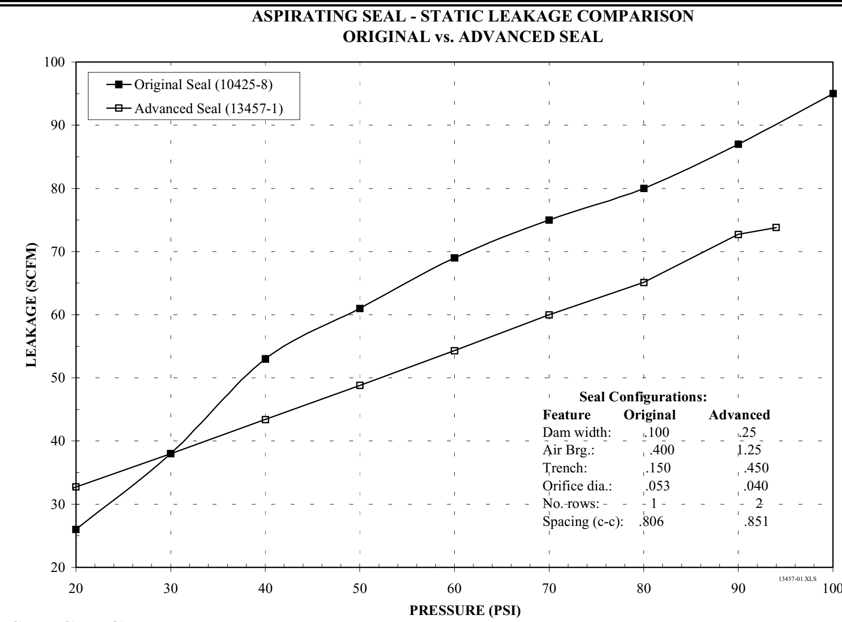
The results of the test demonstrate that the seal performance is very close to the analysis for film clearance measurements.

Test: 1.1 mils (static test @ 30 psid)

1.3 mils (dynamic @ 30 psid & 1,000 rpm, interpolated film clearance)

Analysis: ~ 1.5 mils (30 psid)

Static Leakage - Original vs. Advanced Seal



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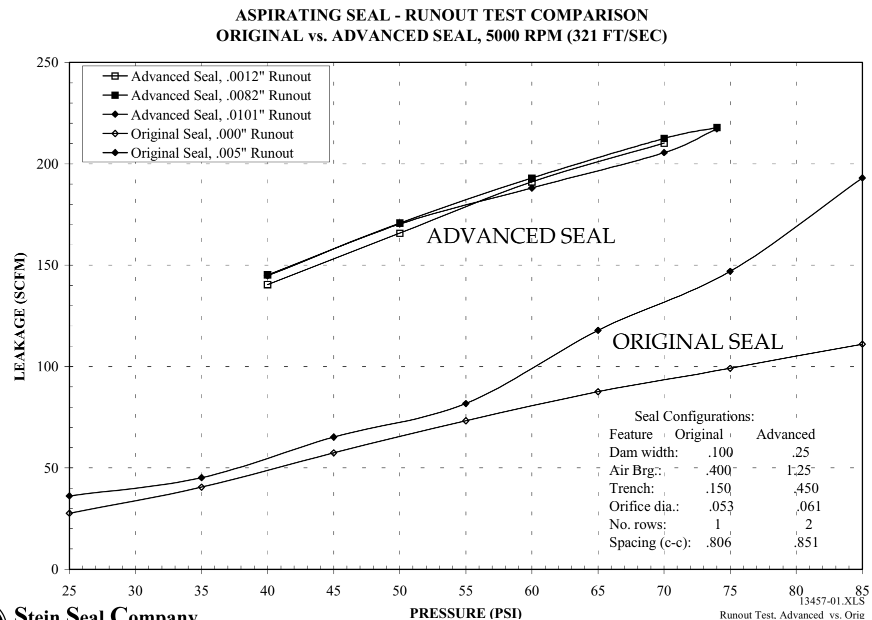
This graphs depicts the Pressure vs. Leakage for the Original and Advanced aspirating seals.

The significance of this graphs demonstrates that the improved gas film stiffness does not affect the seal leakage or gas film clearance performance. Yes, there is a seal leakage difference between the two curves shown above, however, enlarging the air bearing holes in the advanced seal will make the seal operate with a slightly higher film clearance, hence, increasing the leakage.

Rotor Runout Test – Original vs. Advanced Seal



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This Pressure vs. Leakage graph depicts the dynamic seal performance with rotor runout for both the Original and Advanced seals. The shaft speed for the dynamic test was 5,000 rpm (321 ft./sec.)

Advanced Seal

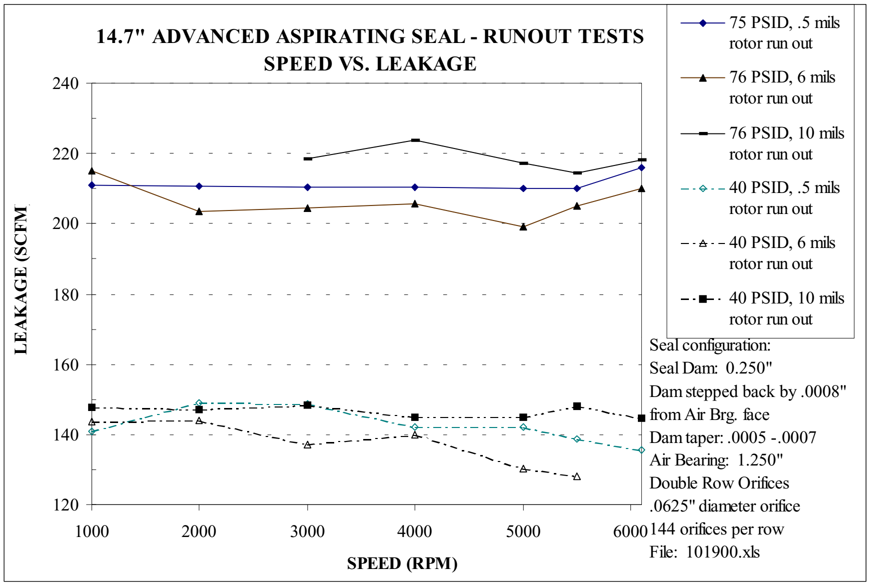
Leakage (and film clearance) are closely matched for the dynamic test conditions with all three runouts: 1 mil, 8 mil, and 10 mil. The seal performed successfully during all dynamic conditions. Follow-on tests included successful tests at the max 6100 rpm speed.

Original seal

The original seal has somewhat varied leakage rates for the 0 mil and 5 mil rotor runout tests. The 5 mil runout test is characterized by higher leakages as air pressure increases. The seal may not be fully tracking the rotor at the 5 mil runout case. Attempts to run 10 mil rotor runout was unsuccessful as the seal rubbed the rotor face.

The results of the test demonstrate that the Advanced seal with higher gas film stiffness permits higher rotor runouts as compared to the Original seal.

Rotor Runout Test - Advanced Seal



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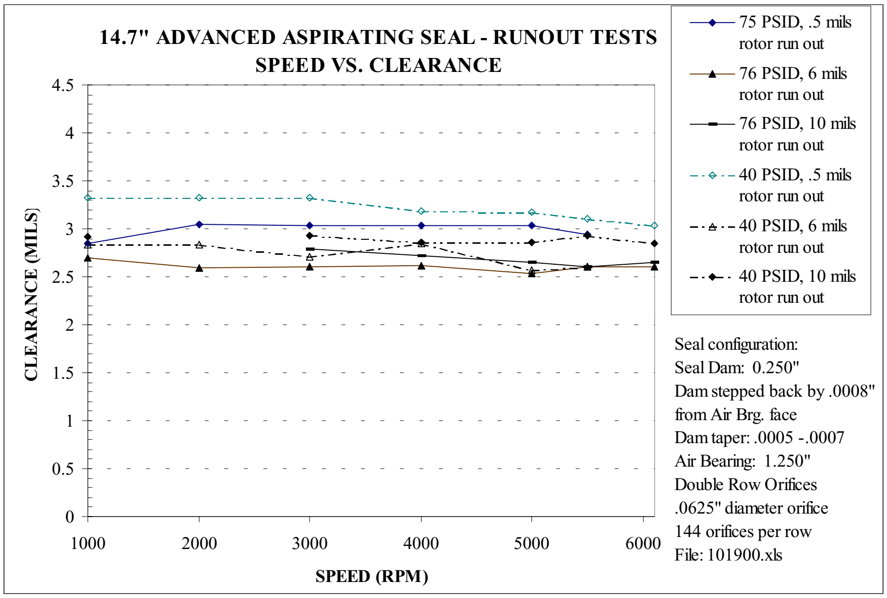
This graph depicts the rotor runout results for two pressure points: 40 psid and 76 psid. The leakage is plotted against increasing rotor speed.

Results show that seal leakage is slightly influenced by increasing rotor runouts.

The seal tracked the rotor successfully with 10 mil rotor runouts.

Rotor Runout Test - Advanced Seal



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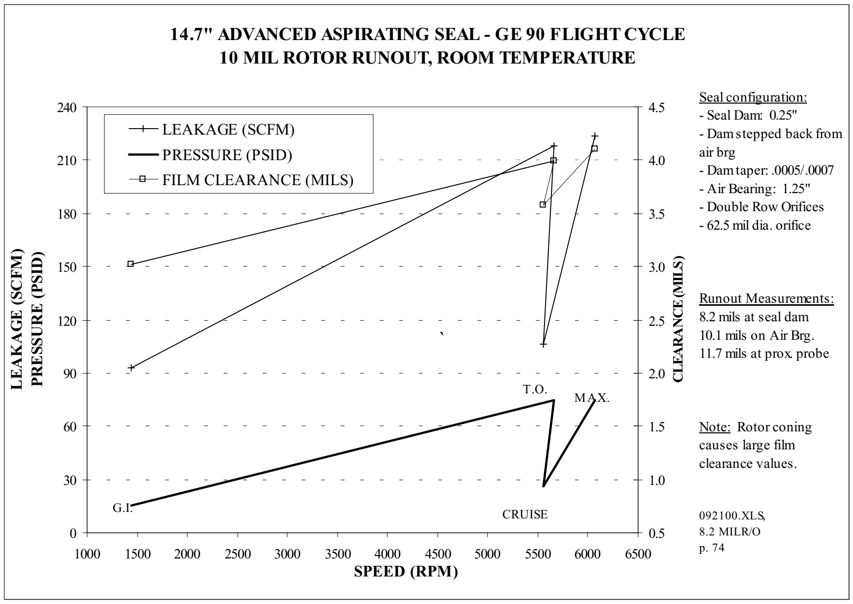
The seal tracked the rotor successfully with 10 mil rotor runouts.

Flight Cycle Results



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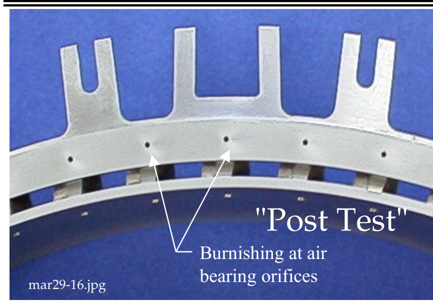
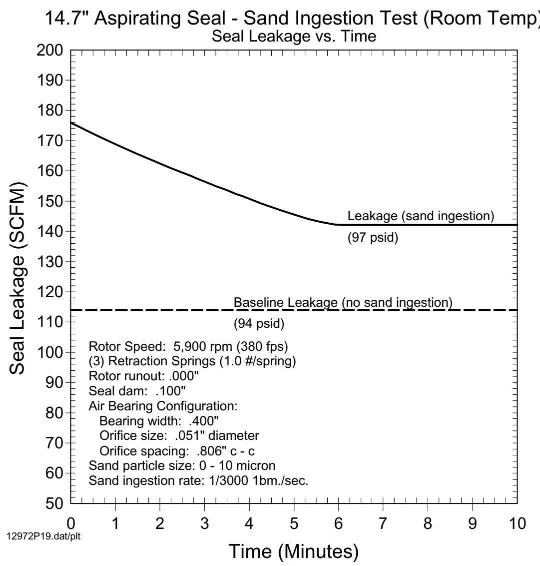
This graph depicts seal performance during a GE-90 flight cycle (room temperature). Three cycles were performed successfully without any problems.

Sand Ingestion Test - Original Aspirating Seal





Test Conditions:

- •Sand delivered at:
  - •1/3000 lb./sec.
  - •10 micron particle size
- •5,900 rpm (380 fpm)
- •97 psid
- •No measurable damage to seal or rotor

The sand ingestion was performed on the Original Aspirating Seal with good results. (This test was performed in 1995)

The sand was delivered into the test head for ten minutes at 1/3000 lbm/sec at 97 psid pressure differential.

The leakage at the onset of sand was approximately 54% higher than the leakage for a test without sand ingestion. As time passed, the leakage settled lower to approximately 24% higher than a seal without sand ingestion.

No damage was noted to the seal faces or orifice holes. It is noted that burnishing did occur near the orifice holes and on the rotor face. Slight burnishing appeared on the seal dam.

Summary

X Seal performance is predictable

X Seal operated successfully to:

- 392 ft/sec (goal: 392 ft/sec)
- 96 psid* (goal: 100 psid) * compressor limit
- 10.1 mil Runout (goal: 10 mil)
- Room temp. (goal: 750 ^{o}F)

X Seal performed flawlessly during extreme conditions

- Rotor Runouts (5 & 10 mil runout) and Rotor Coning
- Sand Ingestion (1/3000th lbm/sec)
- Engine Cyclic Tests (at max rotor runout condition)

X Seal is ready for engine test

Seal performance is predictable, uniform, and validates the seal codes employed in the aspirating seal design. CFD is a valuable tool in the design of the aspirating seal to determine if the rotor flow diverrter is required. CFD correlated the Stein and NASA GFACE seal codes.

Successful dynamic tests roved the Advanced Seal can perform at extreme rotor runout (10 mils), engine flight cycles, and sand ingestion.

The aspirating seal is an ideal alternative to labyrinth or brush seal replacement in gas turbine secondary flow path. The seal operates in high pressure, high temperature, and high speed conditions.

The aspirating seal leakage is an order of magnitude less than the labyrinth or brush seals.

The aspirating seal life can be infinite due to its non-contacting performance.

Unlimited seal life will afford the engine manufactures an extended time between overhauls and reduce costly engine teardowns as currently experienced with labyrinth and brush seals.

Engine integration is the next planned task and is targeted for the GE-90 engine.